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Prospects for joint radio telescope and gravitational wave searches for astrophysical transients

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Abstract. The radio skies remain mostly unobserved when it comes to transient phenomena. The direct detection of gravitational waves will mark a major milestone of modern astronomy, as an entirely new window will open on the universe. Two apparently independent phenomena can be brought together in a coincident effort that has the potential to boost both searches. In this paper we will outline the scientific case that stands behind these future joint observations and will describe the methods that might be used to conduct the searches and analyze the data. The targeted sources are binary systems of compact objects, known to be strong candidate sources for gravitational waves. Detection of transients coincident in these two channels would be a significant ‘smoking gun’ for first direct detection of gravitational waves, and would open up a new field for characterization of astrophysical transients involving massive compact objects.

1. Introduction

Many potential sources of transient gravitational wave (gravitational wave) signals may emit electromagnetic counterparts detectable by existing and planned astronomical instruments. The coincident detection of an electromagnetic signal may provide some of the most compelling evidence for the unambiguous direct detection of gravitational waves, as well as provide important information on the nature of the progenitor system. Short, hard γ -ray bursts (GRB) provide a typical example of such a scenario. These are believed to be the electromagnetic signatures of the coalescence of a compact binary system, consisting of two neutron stars (NS) or a neutron star and a black hole (NS-BH). Gamma ray bursts have been used quite extensively to trigger gravitational wave searches for some time [1, 2, 3] and, indeed, a recent search for gravitational waves from a GRB initially associated with the Andromeda galaxy was able to confidently exclude a compact binary coalescence at the distance of M31 due to the absence of significant gravitational wave emission [1], but did not exclude a binary coalescence event at larger distances.

Searches for gravitational waves which are triggered by electromagnetic observations possess several advantages over un-triggered all-sky searches. Typically, an all-sky search is performed over an entire science run, lasting weeks to months and must search all sky locations for putative gravitational wave signals. An electromagnetically triggered search, by contrast, is usually performed over a much shorter time window lasting a few to several hundred seconds, depending on the nature of the trigger, and the sky-location of the source is usually also known to high precision. The smaller time window increases the search sensitivity since there will be a smaller number of instrumental and terrestrial artefacts in the data, allowing one to tolerate signal detections with lower significance than would be the case for a longer duration search. Knowledge of the expected time of the gravitational wave signal allows one to make a distinction between *on* and *off-source* data. The off-source data, typically taken soon before and soon after the trigger is used to estimate the background rate of potential gravitational wave triggers and the statistical significance of detection candidates in the on-source data. Since the noise from gravitational wave detectors is generally non-stationary, it is important that the data used for background estimation is taken near to the trigger to accurately reflect the noise properties of the on-source data. This, however, is generally not problematic due to the fairly short on-source windows used in externally triggered analyses. As well as the gain in sensitivity from the short on-source window, the sky-location used in electromagnetically triggered searches provides more robust signal-consistency tests in multi-detector searches and significantly reduces the parameter space of the signal.

Observations in radio astronomy have already had a significant impact on the search for gravitational waves. Most significantly, the accurate timing of pulsars in radio has enabled searches for gravitational wave emission from known pulsars [4]. These radio observations permit a significant reduction of the gravitational wave parameter space, resulting in a more sensitive search. Recently, the gravitational wave emission from the Crab pulsar has been bounded to be significantly below the spin-down limit [5]. In addition, observations of pulsar glitches [6, 7] have prompted searches for gravitational waves emitted at the time of the glitch [8].

In this paper, we advocate the extension of the joint radio and gravitational wave search effort to include transient signals in the radio band. Until now, there have been no completely systematic searches for transient radio signals but there are tantalising

hints of a significant population of transients [9] which a new generation of radio telescopes and arrays are ideally positioned to observe. Given the nascent state of the field, there is great uncertainty regarding the nature of the progenitor of many radio transients. Several of the proposed sources of radio transients are also expected to be strong and, in some cases, well-modelled sources of gravitational waves. The potential for serendipitous discovery of new gravitational wave and radio sources, as well as the existence of theoretically modelled mechanisms for radio emission associated with known classes of astrophysical objects, provide strong motivation for proposing a joint gravitational wave and radio observation effort. On top of this, the astrophysical information encoded in the radio and gravitational waveforms will likely be complementary. Thus, as with many multi-wavelength or multi-messenger observations, combining the data from these two different observing channels will enhance the astrophysical understanding of the source.

The paper is structured as follows: in section 2 we outline the observational capabilities both in radio and gravitational waves; section 3 introduces a number of proposed theoretical models predicting both radio and gravitational wave emission from a number of sources; in section 4 we present the search methods that could be utilized in a joint GW-radio search and finally section 5 provides a summary and future prospects.

2. Search tools: radio telescopes and gravitational wave interferometers

2.1. Radio telescopes and recent radio transients survey activity

Radio telescopes fall into two categories — dishes and aperture synthesis arrays. We begin by enumerating in Table 2.1 some of the key specifications of radio telescopes proposed for use in joint searches and subsequently describe them in further detail below.

Instrument	Band	Max. sensitivity	Field of View	Slew Time
LOFAR	40-240 MHz	2.2 mJy	186 deg ²	Software
ETA	29-47 MHz	10 Jy	~ 400 deg ²	Software
NRAO Green Bank	1.15-1.73 GHz	~ 1 mJy	0.027 deg ²	18°/minute
Arecibo	312 MHz - 10.2 GHz	~ 0.5 mJy	0.063 deg ²	< 16 min

Table 1. Observational capabilities of some of the radio telescopes proposed for a joint GW-radio search effort. The aperture synthesis arrays like LOFAR and ETA have wide fields of view operating in relatively narrow frequency bands whereas the single dish telescopes like NRAO Green Bank and Arecibo have significantly decreased fields of view but can operate within much broader frequency bands. Radio flux sensitivity is given in Jansky ($1 \text{ Jy} = 10^{-19} \text{ erg m}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$). The slew time is how fast the telescope can turn around its symmetry axis to track a sky location.

Low Frequency Array (LOFAR) LOFAR is a UHF antenna array recently commissioned by a Dutch consortium lead by the Netherlands Institute for Radio Astronomy (ASTRON) and the University of Groningen. The instrument has made its first observational trials at the end of August 2009 and according to the latest news from [10] the first international observational effort has just been completed.

The instrument and the capabilities afforded by the design are discussed elsewhere [11]. Briefly, the design calls for the deployment of 41 ground stations centered in the Netherlands and further stations extending throughout western Europe. Each ground station comprises of an array of sensors, including between 48 and 96 each of “low-band” and “high-band” antennae[‡] having usable bandwidths of 30-80 MHz and 120-240 MHz respectively and a maximum sensitivity of 10 mJy. One of the key science projects of LOFAR is to search for radio transients. Potential sources include X-ray binaries, GRBs, SNe and AGN.

Eight-meter Transient Array (ETA) The Eight-meter-wavelength Transient Array [12] has been constructed and operated by researchers at Virginia Tech. This instrument is designed specifically to detect low-frequency radio transients, covering the band 29–47 MHz with full-bandwidth sampling. Its flexible signal processing system supports a number of modes by phasing its individual dipole antennas, but it will typically be operated with two 30-degree-wide synthesized beams to do a broad continuous search.

Green Bank NRAO The Green Bank Telescope (GBT) is the world’s largest fully steerable radio telescope [13]. GBT is located at the National Radio Astronomy Observatory’s site in West Virginia, USA. GBT is a 100-meter telescope on a wheel-and-track design that allows the telescope to view the entire sky above 5 degrees elevation.

Arecibo The Arecibo radio telescope in Puerto Rico, USA, is the world’s largest and most sensitive radio telescope (312 MHz - 10.2 GHz and 0.5 mJy sensitivity [14]). It is part of the National Astronomy and Ionosphere Center (NAIC) operated by Cornell University. The telescope itself consists of a 305 meter diameter fixed primary reflector, with a suspended platform containing secondary and tertiary reflectors along with various receivers. The telescope can be pointed within 20° of zenith by moving the suspended platform, with a slew rate of 24°/minute in azimuth and 2.4°/minute in zenith angle. The secondary and tertiary reflectors correct for spherical aberration.

Systematic surveys of the transient radio skies are expected to be performed in the near future at a greater rate than in the past [9]. The unexpected results from such past surveys include discoveries of completely new radio sources (e.g. Rotating Radio Transients, [15]). As an example, in the summer of 2007 Green Bank Telescope took a survey of the northern sky at 350 MHz which covered 12,000 sq degrees. This survey [16] was called the drift-scan survey because it was done while the azimuth track was being refurbished. Data from this survey has thus far uncovered 25 new pulsars including 5 new millisecond pulsars. This data is still being searched for new pulsars and radio transients. This shows the sheer diversity and abundance in new radio sources that can be uncovered by doing a rather short but systematic survey and reveals the potential of a multi-messenger search.

[‡] International stations further from the core group in the Netherlands will add more antennae.

2.2. Gravitational wave interferometers

A global network of gravitational wave interferometers has now been constructed and is taking data. The instruments constituting this network include the Laser Interferometry Gravitational Observatory (LIGO), which operates two observatories in the USA [17]; the French-Italian Virgo detector [18], based in Italy; the British-German GEO600 detector in Germany [19] and the TAMA300 detector in Japan [20]. Data from these detectors has been acquired and analyzed over the past decade. These detectors have achieved or come close to their design sensitivities, and an extended science run of the LIGO, GEO and Virgo detectors was completed over 2005 to 2007 (known as S5 in LIGO/GEO and VSR1 in Virgo). The detectors achieved a strain sensitivity of better than $10^{-22}/\sqrt{\text{Hz}}$ at their most sensitive frequencies (around 100 Hz). This can be translated into sensitivities to various sources, for example the LIGO detectors in S5 were sensitive to optimally oriented and located (i.e. overhead the detector) binary neutron star signals to a distance of 35 Mpc, and hundreds of Mpc for more massive compact binary coalescences. For short-duration, narrow-band transients, such as the gravitational wave signal one may expect from core-collapse supernovae, this sensitivity corresponds to a gravitational wave energy as low as $10^{-8} M_{\odot} c^2 \sim 2 \times 10^{46}$ erg for galactic events and $0.1 M_{\odot} c^2 \sim 2 \times 10^{53}$ erg for events in the Virgo cluster at 16 Mpc.

Following the S5/VSR1 run, the LIGO and Virgo detectors have been technically upgraded to enhanced configurations, and the latest science run (S6/VSR2) began in the summer of 2009, aiming at collecting data at better sensitivities than S5/VSR1. Following this data taking period, both LIGO and Virgo detectors will be upgraded to advanced configurations with approximately ten times the strain sensitivity of the initial detectors. For sources distributed uniformly in volume, this corresponds to a sensitivity to a thousand times as many sources. In terms of energy, the sensitivity will be $\sim 10^{-10} M_{\odot} c^2 \sim 2 \times 10^{44}$ erg for galactic events. The advanced detectors are expected to begin acquiring scientific data by 2015.

3. Radio and Gravitational Wave Sources

Joint observation of gravitational waves and their radio afterglow requires a mechanism for the prompt generation of a radio counterpart to the gravitational wave signal. Furthermore, to avoid self-absorption by the source, models yielding coherent radio emission are favoured. The prospects for detecting gravitational waves from a given progenitor depend on the details of the underlying engine, which in many cases are still uncertain. To pursue a joint radio and GW analysis, one requires a reliable estimate of the delay between the gravitational and radio waves, given by the dispersion measure of the media in which the wave travels. There are several possible progenitors for emission in both gravitational and radio waves, two of which are discussed below: coalescing neutron star binaries and short hard GRB afterglows. We conclude this section with a brief discussion of the effects of dispersion on the radio signal.

3.1. Neutron Star Binaries

Binary neutron stars are one of the most promising candidate sources for gravitational waves. Indeed, the observations of several binary pulsars provide strong evidence for the emission of gravitational waves from these systems [21], as well as an estimate of

the rate of such coalescences in the nearby universe [22, 23]. The waveform emitted by a coalescing neutron star binary system has been calculated to great precision in the post-Newtonian formalism [24]. Initial and enhanced detectors are sensitive to the signal to tens of Mpc while the advanced detectors will be sensitive to hundreds of Mpc. Several gravitational wave searches for coalescing neutron star binaries have already been performed [25, 26]. At the time of writing, there has been no confirmed direct detection of gravitational waves using purpose-built detectors. However, the upper limits obtained on the rate of binary coalescences are now approaching those predicted by astrophysical arguments. The rate of such coalescences observed in the advanced LIGO and Virgo network is expected to be tens per year.

There are a number of models for the emission of radio waves during the late stages of a compact binary inspiral phase or during their coalescence, making these an ideal source for joint radio-GW searches. We discuss two classes of radio emission models below, based on the predicted emission mechanism.

Radio emission due to strong magnetic fields The first class of models require one of the neutron stars to possess a large magnetic field ($10^{12} - 10^{15}$ G). This type of neutron stars, called magnetars, represent a fraction of 10 % of the known population of neutron stars [27] and 18 have been discovered of which eight are Soft Gamma Repeaters (SGRs) and ten are Anomalous X-ray Pulsars (AXPs) [28], all of them isolated objects. According to [29] binary systems with a magnetar and a compact companion may account for 1 % of the total number of neutron stars in the universe.

The model described in [30] assumes the binary neutron star system is composed of stars with (approximately) equal masses and radii in the final stages of inspiral. One of the two NS is required to be a magnetar, with magnetic field $B \sim 10^{12} - 10^{15}$ G, with the second star's magnetic field significantly weaker. Their spins are neglected. By modelling the stars as perfect conducting spheres, it can be shown that as the companion orbits in the magnetic field of the magnetar, a magnetic dipole is induced in the companion and dipolar radiation is emitted. The expected maximum in source luminosity is of the order of $L_{\text{max}} \sim 10^{41}$ erg/s. It is thought that, in analogy with the pulsar model, a fraction of this energy will be radiated in radio band with an observable flux equal to the flux from the Crab pulsar (PSR B0531+21) at a distance of 2 Mpc. The Crab pulsar is located at a distance of 2 kpc [31] and its radio flux at the 400 MHz pulsar reference frequency is 650 mJy [32]. For a source placed at 100 Mpc, this model would predict a radio flux of $F_{\nu} \sim 0.3$ mJy at a frequency of 400 MHz, too low for a detection, but for sources at 10 Mpc or less the flux would be within the detection range of existing radio telescopes.

In a second model [33], the magnetar's companion is assumed to be a rapidly spinning recycled pulsar §. The magnetar is a non-recycled slow-spinning pulsar ($P \sim 10 - 1000$ s). As before, the orbital and rotational motion of the companion result in an induced dipolar electric field on its surface. The majority of the energy lost by the neutron star is converted into plasma, and later radiated. Given the lack of a complete theory for the emission, the authors assume that $\epsilon \sim 0.1$ of the initial beam energy is radiated in radio band at a reference frequency of 400 MHz (this frequency and efficiency are chosen in analogy with radio pulsar observations). The maximum luminosity would be $L_{\text{max}} \sim 10^{35}$ erg/s, a maximum observable flux of the

§ A recycled pulsar is a pulsar with a very short spin period $P \sim 1 - 100$ ms, low magnetic field and low spin-down rate, often found in a binary system; recycled pulsars are pulsars which have lost energy and spun down, and then been spun up again by forming a binary system with a companion.

order $F_\nu \sim 2 \text{ mJy}$ for a source placed at 100 Mpc. The radiation is thought to be emitted isotropically with a spherical symmetry around the low-field companion, so no collimation is assumed.

Plasma excitation through relativistic magnetohydrodynamics It is well known (see e.g. [34, 35, 36, 37]) that, within relativistic magnetohydrodynamics (MHD), gravitational waves will generically cause excitations of waves in the fluid. Specifically, they will excite three wave modes in the fluid: Alfvén waves, fast and slow magnetosonic waves. Thus, in astrophysical situations with strong gravitational waves travelling through strongly magnetized plasmas [37], energy can be transferred from the gravitational field to the plasma. However, the MHD modes are initially excited at the same frequency as the emitted gravitational waves. The challenge then is to determine whether there will be sufficient up-conversion to higher frequencies that the energy might escape as electromagnetic radiation.

In [36, 37] the authors argue that this process could lead to an observable radio signal associated to binary neutron star coalescences. The inverse Compton scattering of the MHD wave by a relativistic outflow of secondary particles will lead to the emission of radiation. When the binary is close to face on to the observer, this radiation will be observed at radio frequencies, within the sensitive band of radio array detectors such as LOFAR. The nature of the signal predicted in [36] is an incoherent burst of radio waves at 30 MHz with a bandwidth of 30 MHz, an in-source power of $P \sim 10^{47} \text{ erg/s}$, and a duration of roughly 3 minutes. For a source located in the Virgo cluster ($\sim 16 \text{ Mpc}$) the predicted fluxes lie in the $F_\nu \sim 10^6 \text{ Jy}$ region. Due to the very efficient damping mechanisms predicted in parallel to this model, the detected flux will most probably be much smaller, but still within the sensitivity of LOFAR. Also, the authors of the model consider the electromagnetic radiation to be collimated with a normal vector parallel to the normal at the plane of the binary. A lack of collimation would render the radio emission invisible to LOFAR.

It is worth mentioning that these two phenomenological model categories do not exclude each other: radio emission due to the presence of a highly magnetized neutron star and its subsequently induced magnetic and electric fields is predicted to occur before the binary merger, whereas interactions of gravitational waves with the surrounding post-merger plasma and consequent MHD phenomena will trigger a radio signal after the merger.

3.2. Gamma ray bursts

The coalescence of a binary neutron star or neutron star-black hole system is still the main candidate progenitor of short hard gamma ray bursts (SHB). Also, such mergers produce much stronger gravitational wave emission than other predicted sources, making them some of the most promising candidates for gravitational-wave detections with the first or second generation of ground-based detectors. The afterglows of SHB have been observed in different wavelengths. Short hard GRBs are known for their weak afterglows, making it difficult to secure confirmation of the progenitor. Results have been published on radio afterglows for short hard bursts but the data shows only weak signals hours or days after the burst [38, 39].

Several authors [40, 41, 42] have argued in favour of a radio component of afterglows from short GRBs, namely a radio burst several minutes after the observed GRB. This radio burst is predicted to be a result of synchrotron emission of the

electrons in the post-merger plasma and is thought to have a flux on the order of mJy, which is within the sensitivity of current radio telescopes. In fact, a proposed discriminant [42] of baryon-dominated (as opposed to magnetic-field-dominated) outflows is the presence of a radio flare, stronger than the early optical afterglow, within the first half hour after the burst. The collimation of the radio burst may be an important factor in observing gamma-orphan bursts (in the case that the orientation of the gamma ray burst is not favorable for a γ -detection). The authors of [33] suggest a spherical emission surface whereas [40, 41] consider that the radiation process is highly directional along the gamma-ray emission axis.

Core collapse within massive stars is one of the most widely predicted sources of transient gravitational and electromagnetic radiation. This is the underlying mechanism of supernovae, which occur a few times per century in galaxies like our own. At higher masses this collapse can produce long gamma-ray bursts, which are observed at a rate of 10^{-7} yr^{-1} per galaxy, though the intrinsic rate is likely one or two orders of magnitude higher due to beaming [43]. However, the strength of gravitational-wave emissions from supernovae is quite uncertain. Optimistically it could be as high as $10^{-4} M_{\odot} c^2 \sim 2 \times 10^{50} \text{ erg}$ of energy released as gravitational waves between 500 and 1,000 Hz [44]. Gamma-ray bursts may produce highly-beamed radio bursts within minutes of the gamma-ray burst [41], and supernovae in general may produce electromagnetic afterglows starting hours after the initial energy release.

3.3. Dispersion in the intergalactic and interstellar media and Compton scattering

Radio waves are strongly coupled to charged particles and, therefore, are potentially subject to the effects of self-absorption in ionized material surrounding the source and to dispersion in the interstellar and intergalactic media (ISM and IGM, respectively). Self-absorption effects are more pronounced when the radio emission is incoherent, as with some of the above emission scenarios associated with binary neutron star systems.

Following [45], a radio pulse traveling in the ionised ISM is delayed over its propagation time through free space by a time Δt_{delay} ,

$$\Delta t_{\text{delay}} = 4.1 \text{ ms DM } \nu_{\text{GHz}}^{-2}, \quad (1)$$

where ν is the observation frequency and DM is known as the dispersion measure. This is the integral along the line-of-sight of the electron density between the observer and the source:

$$\text{DM} \equiv \int dr n_e(r), \quad (2)$$

where r is the distance to the source and $n_e(r)$ is the electron number density at r .

Now, the IGM has a much lower electron number density than the ISM, but the radio signal must travel a far greater distance through the IGM ($\sim 100 \text{ Mpc}$ for advanced detectors) than through the ISM where the emission must propagate across only $\sim 10 \text{ kpc}$ for galaxies similar to the Milky Way. In the plane of the Milky Way, the number density of electrons is, on average, about $n_e = 0.03 \text{ cm}^{-3}$ [46]. So the dispersion measure for 10 kpc of ISM equivalent to the disc of the milky way is $\sim 300 \text{ pc cm}^{-3}$. The expected dispersion measure contribution for intergalactic distances is $\text{DM} \approx 100 \text{ pc cm}^{-3}$ [47, 48] and so the dispersion due to the intergalactic and interstellar media along the signal path are comparable. The time delay due to dispersion for a 1 GHz radio signal is estimated to be less than 4s for sources within range of advanced detectors [47]. Taking this number and adding a component

for dispersion in the interstellar medium, we can estimate that dispersion delays of order a few seconds for sources embedded in Milky Way-like galaxies at distances of order a few 100 Mpc may be expected. Since the time delay is inversely proportional to the second power of frequency, lower-frequency signals may be delayed by many minutes; however, the time of emission may still be inferred from a broadband signal by extrapolating the delay-vs.-frequency function to infinite frequency. We therefore retain the benefits of a triggered search.

In the case of short hard GRB radio afterglows, apart from dispersion, the radio waves emitted by such bright sources may suffer from induced Compton scattering within the source, phenomenon that will cause a significant dampening of the signal. Detailed in [49], the induced Compton scattering is the main limiting factor when the region around the progenitor is not dense but when one still considers the scattering effect of a tenuous circumburst interstellar medium. The presence or absence of a radio emission provides an excellent constraint on the Lorentz factor of the GRB outflow during the very early stages of its outburst, hence providing information on the energetics of the progenitor and its nature.

4. Joint radio-GW searches

There are two ways in which the coincident detection of a radio-GW event can be made: either by following up radio transients in existing gravitational wave data, starting with existing radio transients detected during the past and present science runs, or by using the prompt detection and localization of gravitational waves as initial trigger and *alerting* the radio telescopes to point in the direction where the gravitational wave was observed. We will discuss each of these in turn.

4.1. Follow-up of radio transients in archived gravitational wave data

As we have argued earlier, performing an electromagnetically triggered search of gravitational wave data has several advantages over the all sky, all time searches. The external trigger allows for a significant reduction in the data to be searched, both by restricting the time duration and also the sky position. This reduction in parameter space leads to a corresponding increase in the sensitivity of the search. Given the theoretical models presented in the previous section, there is a clear motivation for performing a follow-up observation in gravitational wave data of radio triggers. Gravitational wave data is routinely archived and also, there is no inherent time restriction in performing the search. Indeed, if there are radio transients identified at times that overlap previous gravitational wave detector science runs, it is possible and much desired to search the gravitational wave data around these times.

An outstanding challenge is to obtain a better understanding of the relative timing of the radio and GW signals. Once the GW time window is greater than a few hours, much of the benefit of performing a follow-up style search is lost. Thus, it is imperative that we improve our understanding of the various models presented above to obtain good estimates of timing differentials between GW and radio signals. An interesting aspect of the follow-up of radio triggers is that for each event we will have an estimate of the dispersion measure. By measuring the dispersion, it should be possible to correct for any time delay of the radio signal. Furthermore, this should provide an independent measure of the distance, which could be compared with any GW observations.

The follow-up searches begin with a list of radio transients; for each one a GPS time, the duration, the energy of the burst, the dispersion measure and sky location are recorded. For each event, we advocate the use all available LIGO/Virgo data at the time of the event to follow-up these events. Given the source models discussed in section 3 we propose the following gravitational wave searches:

- Search for compact binary coalescence. There is an argument to focus this search on binary neutron star signals. It should be straightforward to apply a very similar search method to that used for searching for gravitational waves associated to short GRBs [1]. Although there are fewer models predicting radio emission from neutron star-black hole and black hole-black hole binaries, it is straightforward to extend the search to include these systems as well. Interestingly, in the absence of a detection, it should be possible to set a lower limit on the distance to the source assuming that it is a binary merger. It should then be possible to compare this limit to the distance inferred from the dispersion measure; we may be able to say with some confidence that a given radio burst was *not* caused by a binary merger.
- Search for unmodeled bursts of gravitational waves. When the radio burst is well localized in the sky, it should be straightforward to make use of the same methodology as has been previously applied in the search for gravitational waves associated with GRBs [2]. Some radio antennae, for example the ETA radio array, will mainly operate in a wide-area burst-search mode and therefore will not provide a good sky localization. In this case, the simplest search would be a coarse time and sky location coincidence between radio and gravitational wave triggers from a standard excess-power style, all sky burst search.

4.2. Gravitational wave events followed-up by radio observations

Gravitational wave antennae have broad-lobed antenna patterns covering tens of degrees on the sky per instrument and it is not possible to estimate a source's sky-location with a single instrument. Rather, it is necessary to use a network of at least three gravitational wave detectors to reconstruct a single region on the sky. This region may then be imaged by electromagnetic instruments in the hope that the gravitational wave signal can be associated with some distinctive electromagnetic signature, such as a γ -ray burst. However, it is important to remember that the intrinsic pointing accuracy of the LIGO/Virgo gravitational wave network is still on the order of tens of square degrees [50], even using a network of detectors.

For following up gravitational wave events then, aperture synthesis arrays such as LOFAR and ETA offer some key advantages. Signals from multiple antennae are correlated to synthesize a beam far narrower than the antenna pattern of a single antenna, which may be as simple as a dipole. The parameters of the correlation may be tuned to allow beams as wide as 30 degrees with resolving power as good as 0.5 arc seconds. Reaction time of the instrument is dependent on the software driving the correlator. A key difference between aperture synthesis arrays of radio telescopes and a gravitational wave detector network is that the sampling rate in the radio precludes archiving data for more than a few seconds, so that there is no look-back capability. Thus, the key challenge for this search is the rapid analysis of the gravitational wave data, to allow for timely pointing of radio arrays.

5. Summary

In this paper we have presented the case for joint gravitational wave and radio analysis between data from the gravitational wave detectors available to the LSC/Virgo collaborations and a variety of radio astronomical instruments. It encompasses a variety of projects, some of which are minor extensions of existing projects in the optical or gamma ray observations, whilst most of the others make use of existing software or collaborations.

A series of scientific factors motivate such a coincident search: it is a logical evolution of the previously started gamma ray coincident searches, extended to the radio band; there are a series of published theoretical models that predict radio events preceded or followed by gravitational wave emissions; computationally speaking, the data analysis pipelines are already in place for such a task. Although, in broad lines, the proposed observational and data analysis mechanisms are similar to the ones that already exist as multi-messenger projects and are a logical evolution of the multi-messenger concept itself in exploring all the available electromagnetic bands, a coincident detection of radio and gravitational wave transients poses a set of very particular issues to this type of search. One of these issues is that the theoretical models considered are far from being confirmed by astronomical observations; the diversity of the models suggests a very broad approach from the side of the theorists and a burden for us, the astronomical observers, in confirming or disconfirming the models in an environment where choosing a particular model may increase the sensitivity of the whole search. Another issue is that, even if most of the computational tools are in place, the initial search parameters are still to be decided, e.g. the time window around a radio transient that should be searched over in gravitational wave data, the dispersion measure based on the IGM and ISM number density, the mass distribution and populations of the compact objects thought to be the sources of both radio and GW transients. Thus, there is much to be explored in the near future.

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